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Estimation of the Leaf Area Index and Light Intensity in a Brazilian Tropical Forest Fragment

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Abstract
In order to apply techniques aimed at the restoration and recovery of forest fragments, it is necessary to understand the ecological succession of the respective biome and the factors influencing its dynamics. Luminosity is one of the key factors for comprehending the cycle of native forests, influenced not only by climatic seasonality but also by the canopy structure and forest strata. The Leaf Area Index (LAI) is directly linked to plant growth conditions. The objective of this study is to map the distribution of LAI in the canopy of a Mixed Ombrophilous Forest fragment using non-destructive methods and to quantify luminosity. The research was conducted around the University Campus of the State University of the Midwest - UNICENTRO, in the municipality of Irati, Paraná, Brazil. These variables underwent numerical terrain modeling using the free software SPRING, resulting in two spatial representations, each containing four classes for each variable. The data underwent statistical analysis using Spearman's and Pearson's correlations, resulting in coefficients of 0.89 and 0.9, respectively. Thus, both variables are strongly linked, with LAI as the independent variable and luminosity as the dependent variable. The use of numerical terrain modeling for the variables proved appropriate, as it allowed the expression of visual features that can be observed within the experimental area.

Keywords
Native Forest — *Araucaria angustifolia* — Geographic Information Systems.

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1. Introduction

The Mixed Ombrophilous Forest (MOF) is a phytogeographic unit found in the Southern region of Brazil, encompassing the states of Paraná, Santa Catarina, and Rio Grande do Sul. It features the *Araucaria angustifolia* (Bertol.) Kuntze species as its characteristic tree and is also known as the Araucaria Forest (Veloso et al., 1991). However, this type of forest has suffered anthropogenic activities that led to its fragmentation. Logging, agricultural expansion, and urban sprawl are examples of human actions that have contributed to the reduction of native forest areas (Medeiros et al., 2005)

Initially, almost half of Paraná's territory was covered by Araucaria Forest (Figueiredo Filho et al., 2010). Research indicates that the forested area in Paraná encompasses about 3.4 billion hectares, of which approximately 17% are MOF, with only 13% of these forests in good condition (Sanquetta, 2012). MOF holds 40% tree endemism (RODERJAN et al., 2002), underscoring the significance of restoration and preservation efforts.

Recovery and preservation of native forests necessitate phases like forest understanding. Familiarity with the forest, its components, and factors influencing growth or forest succession cycle are integral to sustainable management development.

Regarding natural forests and their succession cycle, luminosity and soil conditions are pivotal factors, significantly influencing regenerative processes (Alvarenga et al., 2003). Thus, monitoring and modeling vegetation dynamics within climatic variability and temperature changes necessitate a robust dataset of biophysical variables that explain vegetation operation and forest structure (Zhu et al., 2013).

Alterations in canopy structure (due to storms, droughts, or management practices) change light intensity penetrating the forest, control water interception, disperse solar radiation, affect gas release rate, and impact plant productivity enabling or hampering regeneration (Brokaw et al., 1982; Bréda, 2003).

The Leaf Area Index (LAI) is projected area of both sides of a leaf within a specific canopy area per unit

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ground area (m^2/m^2) (Chen & Black, 1992). It is a crucial parameter describing ecosystem condition (Nackaerts, et al., 2000). LAI serves as a biophysical parameter for plant growth in agronomic models (Goel, 1988; Teruel; Barbieri; & Ferraro Jr., 1997; Doraiswamy et al., 2004; González-Sanpedro et al., 2008). Its variation during an agricultural cycle aids evaluating how aerial vegetation (leaf area) occupies the available ground area (Lucchesi, 1987). Increased leaf area enhances solar energy utilization for photosynthesis and productivity assessment (Lucchesi, 1987), estimating evapotranspiration and biogenic emissions (González-Sanpedro et al., 2008).

LAI can be directly measured through a destructive method or indirectly using non-destructive methods. The former is laborious and time-consuming, requiring the targeted vegetation's removal. The latter uses processes and equipment to estimate values through mathematical equations (Bréda, 2003; Coelho Filho et al., 2012).

Surveying entire forests to quantify attributes over extensive areas is demanding in terms of time and funds. Hence, sampling techniques are introduced to reduce investment, save practical procedure time, and ease quantification proportional to total area size (Spurr, 1952; Péllico Netto & Brena, 1997; Sanquetta et al., 2019).

Techniques that facilitate and offer new problem visualization approaches are crucial. Map utilization exemplifies practicality in area comprehension. Geographical Information Systems (GIS), a collection of tools for acquiring, storing, manipulating, synthesizing, editing, and emitting spatial information (Burrough, 1986; Câmara et al., 1996; Ferreira, 2006), are essential technologies to tackle complex phenomena like forests and their factors.

A GIS comprises four aptitude groups: input, management, manipulation and analysis, and output (Aronoff, 1989). Numerical Terrain Modeling (NMT) or Digital Terrain Modeling is a GIS tool for calculating slope, cross-sections, lines, and variable associations linked to engineering and more (Câmara & Ortiz, 1998). NTM represents a computational mathematical depiction of spatial phenomena distribution within an Earth surface region (Felgueiras & Câmara, 2005).

In this context, this study aimed to map the Leaf Area Index (LAI) distribution within a fragment of the Mixed Ombrophilous Forest (MOF), using two non-destructive methods one for LAI quantification and the other for measuring luminosity (klx).

2. Material and Methods

2.1 Study Area

This study was conducted in the vicinity of the Campus of the State University of Centro-Oeste – Unicentro, in the municipality of Irati (Figure 01), in the state of Paraná, Brazil. The municipality of Irati is situated approximately 153 km away from the capital city, Curitiba.

According to (Mazza; Mazza; & Santos, 2005) and as per the Köppen classification, the climate of the region falls under the Cfb type, characterized as humid subtropical mesothermal, with cool summers, frequent and severe frosts, and no dry season. The forest formation that covers the region is referred to as Montane Mixed Rainforest, characterized by advanced secondary vegetation, with main species including *Araucaria angustifolia* (Bertol.) Kuntze, *Ilex paraguariensis* A.St.-Hil., *Ocotea odorifera* (Vell.) Rohwer, *Nectandra grandiflora* Nees, *Ocotea porosa* (Nees & Mart.) Barroso, *Casearia decandra* Jacq., and *Cedrela fissilis* Vell (Rode, 2008; Stepka et al., 2011; Sawczuk, 2009; Lisboa, 2014).

The research was conducted within a fragment of Montane Mixed Rainforest in an advanced stage of secondary vegetation succession, meaning it comprises a forest with multiple strata, including trees up to 15 meters in height, affected by human intervention. Within the native forest fragment, a one-hectare area was delineated for the study, referred to as a 'plot' for ease of comprehension.

2.2 Experiment Setup

The plot was laid out in the shape of a flat geometric figure, represented by a square with dimensions of 100 x 100 m. The methodology for establishing the sample units depends on a combination of factors that need to be considered when adopting the size and shape of the plots. In this study, due to the nature of point-based collections, each region becomes unique, as photographic canopy sampling and luminosity measurements were carried out at each point, following the methodology described by (Souza et al., 2012).

Trails were opened along the perimeter of the area to facilitate movement. Using tape measures and compasses, the boundary vertices of the area were marked. The boundary vertices were equally spaced from each other, located at 100 meters apart, totaling one (01) hectare. The plot was divided into 25 sample units with dimensions of 20 x 20 m (Figure 02), with wooden pegs inserted every 20 meters along the x-axis (X) and y-axis (Y) directions, totaling thirty-six (36) vertices.

2.3 Photography and Luminosity Measurement

Images of the canopy were captured and luminosity was measured at each of the 36 vertices within the experimental area. Two devices were used for this purpose: a Nikon Digital Camera, model D-3200, with an AF-S DX NIKKOR 18-105mm f/3.5-5.6G ED VR lens, and a

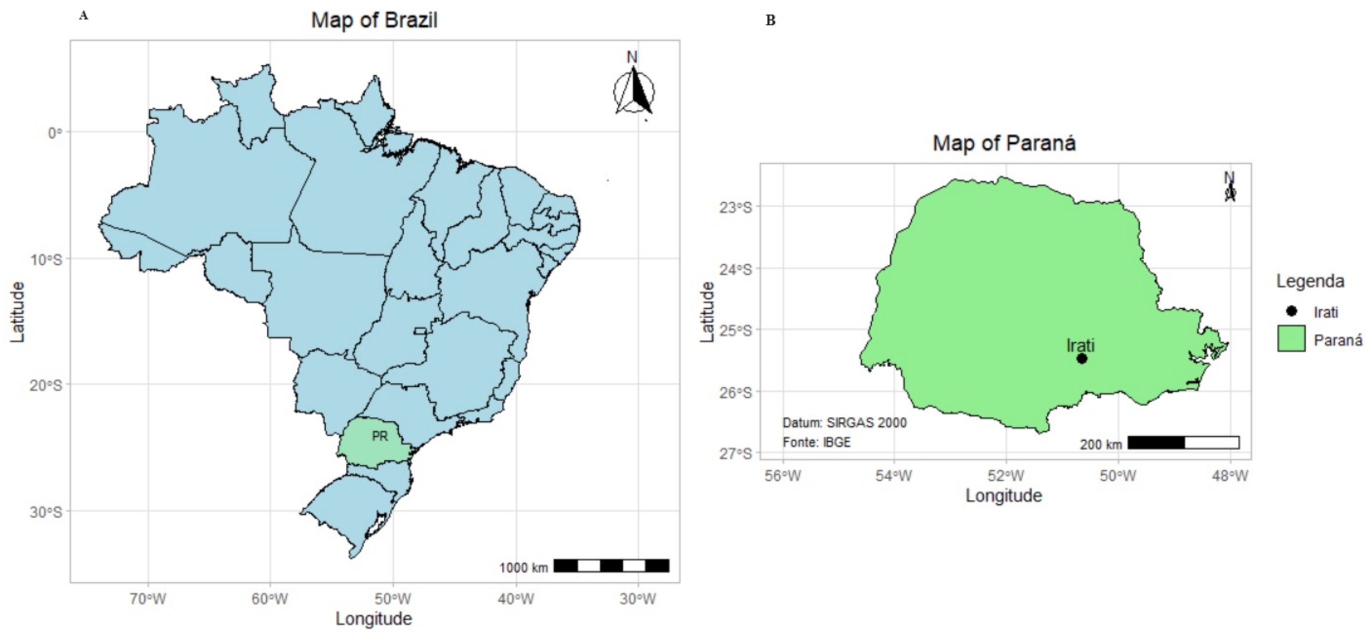

Figure 1. Location map of the municipality of Irati, Paraná, Brazil.

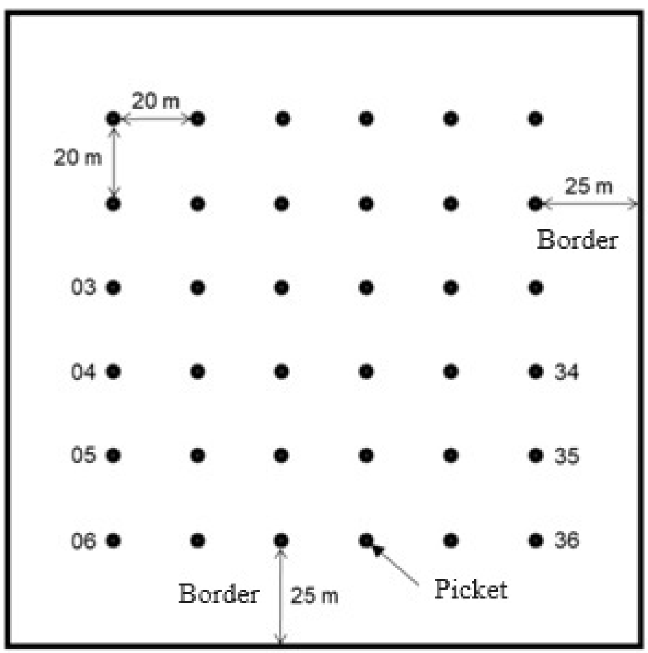

Figure 2. Representation of the components of the experimental area and their distances.

Luxmeter.

The camera was oriented using a compass, indicating the lower point of the lens towards the North direction. It was fixed with the lens at a 180º angle relative to the ground on a tripod to capture canopy images, as suggested by (Giunti Neto et al., 2015). The tripod was set up at a height of 1.30 meters from the ground to prevent image tilting or deviation, with a simple level attached to it. The same authors suggest that photos should be taken between 7 AM and 10 AM to avoid high light intensity days. It's important that the images are captured when the light is in the diffuse field of luminosity, avoiding excessive shadows and direct light (Monte et al., 2007).

The collections were carried out simultaneously for both devices between 8:30 and 9:30 AM on April 25, 2017. The sky in the vicinity of the region was partially covered by clouds with no probability of rain.

The free software "Gap Light Analyzer," developed by the Cary Institute of Ecosystem Studies, was used to obtain the percentage of canopy openness or the percentage of luminosity that passes through the canopy layer by analyzing the canopy images (Frazer; Canham; & Lertzman; 1999).

Four (04) photos were taken at each vertex. After obtaining the photographs, they were individually processed on a computer and analyzed using the "Gap Light Analyzer" software - GLA 2.0. After processing the photographs, the arithmetic average of the values obtained in the processing was calculated, resulting in only one value per vertex.

The device used for measuring luminosity intensity was the Luxmeter. This device was positioned at 1.30 meters above ground level, with the tip of the meter pointing

North. Measurements were always taken by the same person to reduce sampling errors that may arise due to different individuals. The Luxmeter's unit of measurement, according to the International System of Units, is represented by the abbreviation "lx," which corresponds to the perpendicular incidence of 1 lumen on a surface of 1 square meter (lumen/m²).

To achieve greater precision, the Luxmeter was calibrated to use the unit "klx," which represents "lx" multiplied by 1000. Four (04) measurements were taken at each of the 36 vertices, and subsequently, the arithmetic average was obtained, resulting in a mean value per vertex.

2.4 Implementation of GIS for Area Spatialization

A Geographic Information System (GIS) was implemented using SPRING software version 5.4.2, containing cartographic base information of the study area and the locations of the sampling points.

2.5 Digital Terrain Modeling - DTM

For the elaboration of DTMs, the methodology presented by (Felgueiras & Câmara, 2005) was followed. The process of generating DTMs for the variables in question was divided into 4 steps: (a) obtaining the mean values of 'LAI' collections; (b) obtaining the mean values for the 'klx' variable; (c) associating the sample points with the corresponding Z value - that is, the variable - in the spatial database, and (d) generating the models themselves through a method of spatial interpolation.

The method used was the interpolation of the mean elevations of neighboring samples, also known as the nearest neighbor method. This method is the simplest for estimating elevation values of points in a regular rectangular grid.

2.6 Creation of Thematic Maps

Using the DTM for the variables "LAI" and "klx," an exploratory analysis (statistical) was conducted to better understand the data range. Subsequently, classes were determined for the variable data, and colors were assigned to each class. Next, a slicing operation of the DTM was performed to obtain thematic maps for "LAI" and "klx" in classes. Figure 03 presents the operational flowchart for creating thematic maps from regular sample points. This same operational process was carried out for generating thematic maps for the variables targeted in this study.

2.6.1 Statistical Analyses

The data were subjected to analysis using open-source software, including Spring, GLA, PAST, and SAM. Pearson and Spearman correlations were employed between the variables LAI and klx, with klx as the dependent variable, as the quantification of luminosity depends on the presence of "Sunflecks," small openings between leaves and branches in the canopy that increase or decrease light penetration according to their size, i.e., openings in the upper area of the plant. The data were also subjected to linear regression using the R software package.

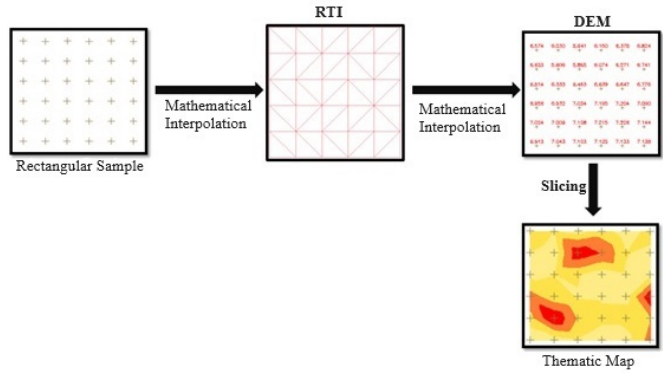

Figure 3. Operational flowchart for the preparation of thematic maps.

3. Results and Discussion

The non-destructive method of obtaining the leaf area index (LAI) proved to be quick and easy to use. It only presented issues related to movement within the area with the equipment mounted on the tripod, due to the presence of small vines and dense undergrowth.

The acquisition of luminosity values (klx) also proved to be rapid and straightforward. However, while handling the Luxmeter, it displayed high sensitivity to light. This sensitivity initially hindered the data collection readings, but it was easily addressed. Through testing, it was found that taking 04 measurements for each point allowed for obtaining a representative average measurement. The LAI values ranged from 5.44 to 7.51 m²/m². These values encompass the entire leaf area, including the leaves in the upper strata as well as a portion of the woody material of the trees, as can be seen in Figure 04 A.

According to Galvão et al. (2015), they studied seasonal variations of the leaf area index (LAI) in a Seasonal Forest, where a range of 6.5 to 3.4 (m²/m²) was obtained. The authors noted that this variation occurred due to a significant loss of the vegetative material comprising the canopy of trees as this component diminishes from summer to winter. The image processing software segregated white pixels from black pixels, thereby performing the LAI calculation based on the area occupied by the black pixels and, simultaneously, generating a mask to avoid edge effects (Figure 04 B). This enabled the verification

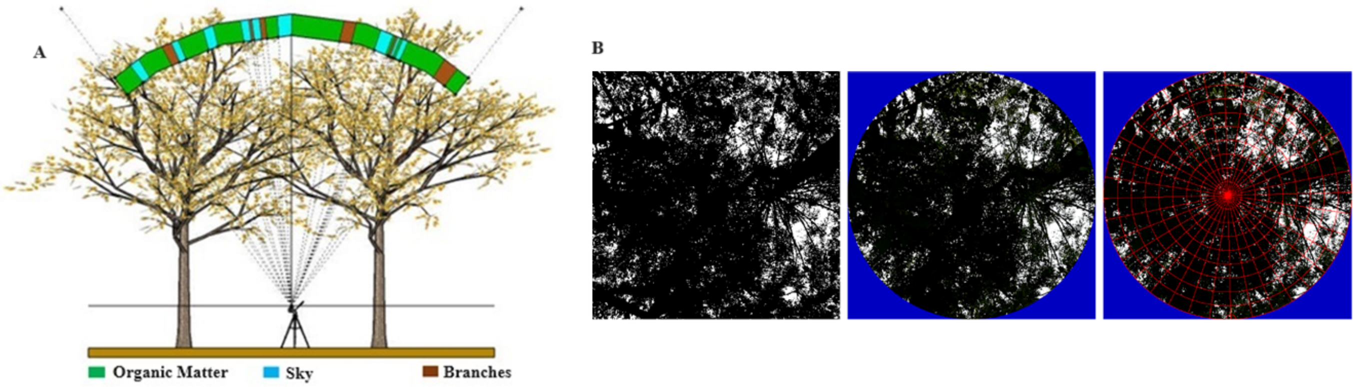

Figure 4. A: Illustration of the components captured by the camera. **B:** Image being processed by the software and mask.

that the software considers all black pixel components as leaf area, regardless of whether they consist of bird nests, branches, trunks, and other elements. As Shinzato, Yoshida, and Duarte (2015) pointed out, the true LAI values obtained by this method tend to align more closely with the results obtained through destructive methods involving leaf collection.

After all the data were obtained and transferred to digital spreadsheets, they were subjected to the generation of digital elevation models. This procedure proved to be efficient as it allowed the generation of thematic spatial representations from numerical, spatialized values, which facilitated the understanding of the values in the form of areas. According to Lima, Almeida and Siqueira (2017) this method enables semi-quantitative analyses by facilitating interactions between variables, serving as a source of information, and the data are generated quickly and can be updated over time due to the generated database. The use of GIS in generating thematic maps simplifies data manipulation by reducing the time required for completion, making it practical and feasible, and GIS also aids in the application of other techniques and methodologies (Serio et al., 2008).

Figure 05 consists of the spatial representation resulting from the slicing of the DEM for the LAI variable, containing 04 thematic classes.

The 1st class has low LAI (red color), the 2nd class has medium LAI (orange color), the 3rd class has high LAI (yellow color), and the 4th class has very high LAI (beige color). In areas occupied by classes 1, 2, 3, and 4, they represent: 439.33 m^2, 1688.22 m^2, 4616.87 m^2, and 3255.58 m^2, respectively. Points P08, P14, and P33, belonging to the 1st class, are located in areas where the canopy structure can be considered open or semi-open. This might be due to tree falling or partial canopy absence, as seen in the area of point P14. The falling and canopy absence were considered natural causes as the research area, in general, shows no signs of human intervention. Point P08 is near a "fissure" in the ground, resembling a channel or erosion groove where rainwater flows. Thus, it's possible to observe a different canopy structure formation compared to other areas. In this point, it's noticeable that trees have more space to develop their canopies, reducing competition for light.

Most of the areas representing the 2nd class are located around the 1st class areas. This could be caused by the falling of climax trees, decreasing the leaf area occupied by the upper canopy boundary set, yet not altering the middle strata where LAI was sampled. The 3rd and largest class in area exhibited a well-formed canopy structure with well-occupied middle and lower strata. Notable points include P15, P17, and P29, where apart from a good middle stratum structure, the characteristic species of this typology, *Araucaria angustifolia*, was observed. At points P20, P25, and P29, the middle stratum consists of broad-leaved trees, and the upper stratum was occupied by the species Parapiptadenia rigida.

The 4th class, despite having a smaller area compared to the 3rd class, exhibited a well-formed understory, middle, and upper strata. These areas mainly consisted of broad-leaved tree species such as *Ilex paraguariensis*, *Luehea divaricata* (Mart.), and *Hovenia dulcis* (Thunberg), with the first two being naturally occurring in FOM and the latter considered an exotic species.

The tests performed in the pre-data collection phase were crucial in understanding how light behaves within the studied fragment. It was observed that light intensity, or luminosity, represented in this work as "klx," varied according to the canopy structure type, the quantity and size of stratum components, and the type of radiation (direct or diffuse) present at the collection point. The collection time followed the description in [34] to avoid

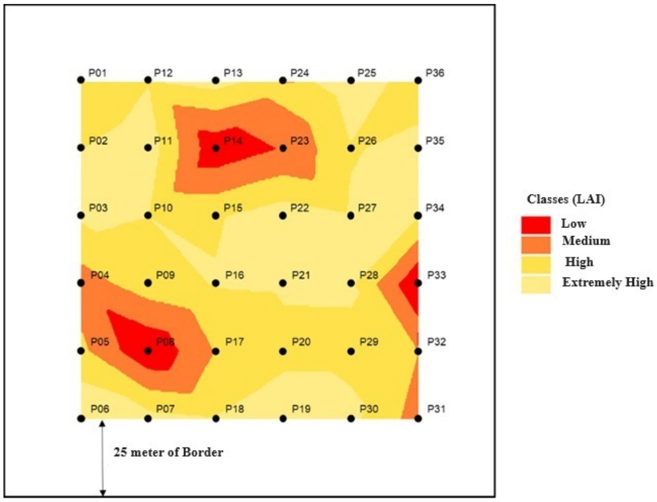

Figure 5. Spatial representation of the NTM and its classes for the variable LAI.

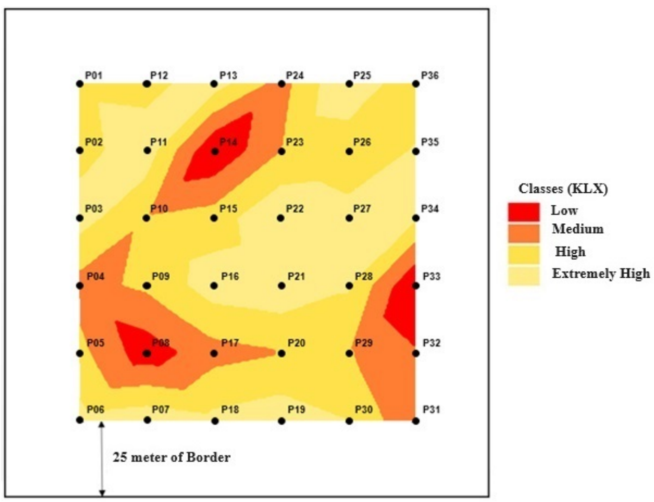

Figure 6. Spatial representation of NTM and its classes for variable klx.

peak periods of direct radiation. However, even at this time, the presence of small clearings and sunflecks at the collection points caused the light intensity to be higher than in other areas.

Figure 06, besides resembling Figure 04-B, represents the spatial representation of the digital elevation model for the variable "klx." This variable can be considered dependent on the canopy structure, or LAI, because the higher the light blockage by the canopy, the lower the luminosity that reaches the understory.

The 1st class has very high klx (red color), the 2nd class has high klx (orange color), the 3rd class has medium klx (yellow color), and the 4th class has low klx (beige color). The areas of the klx classes have sizes opposite to the LAI classes, with 3055.50 m², 4282.09 m², 2194.73 m², and 467.68 m² for classes 1, 2, 3, and 4 of klx, respectively.

The values for klx ranged from 0.31 to 1.90 (lumen/m²), showing canopy structure heterogeneity among the 36 points. The representativeness of this variable varies with the momentary canopy composition. It is believed that during periods of strong winds, the variable might be overestimated compared to moments of lower wind intensity. The device has sensors that are highly sensitive to changes in the canopy caused by the wind.

When comparing the two spatial representations, it was possible to identify that point P02 is in the transition area between classes 3 and 4 for LAI and is in class 2 for klx. Point P17 is in the 3rd class of LAI, considered a high value for this variable, and also in class 3 for klx, also considered high. Point P30 is in class 4, representing a very high LAI value. However, this same point is in the transition area between classes 1 and 2 for klx, containing low and medium values for the klx variable. This might have occurred due to varying light intensity that penetrated the canopy at the time of collection or momentary canopy change, possibly caused by the wind. Points P08, P14, and P33 presented the highest klx values, likely due to the low presence of canopy barriers. Small clearings can be found in this area, caused by natural succession effects.

The mathematical interpolation used in generating the digital elevation model was the nearest neighbor mean, which might have caused an increase or decrease in class areas for the two variables, as seen in points P29, P31, and P32.

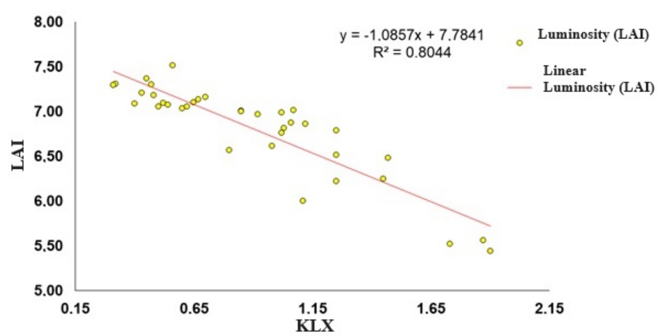

Figure 7. Dispersion of LAI and klx variables.

Correlations were calculated for Pearson and Spearman from the LAI and klx values, resulting in -0.8964 and -0.9009, respectively. The correlation test successfully explained the relationship between the two variables. The predictor variable was LAI, and klx was used as the dependent variable. According to the results, it can be observed that as LAI increases, klx decreases.

A high coefficient of determination (R^2) of 0.8044 was obtained through linear analysis (Figure 07). This indicates that 80.40% of the dependent variable (klx) can be explained by LAI, ensuring reliability in the interaction between the variables.

4. Conclusion

The variables, LAI and klx, are strongly linked based on the obtained statistical results. When using LAI as the predictor variable and klx as the dependent variable, better statistical response was achieved compared to using klx as the predictor.

Through thematic representations, it was possible to visualize the canopy dynamics of the fragment and its influence on the incidence of light reaching the forest interior.

The utilization of numerical terrain modeling for the variables proved to be appropriate, as it allowed the expression of visual characteristics that can be observed within the experimental area.

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Author Statements

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- ✓ There is no evidence of plagiarism in this article.

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